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14. ABSTRACT
A key factor for responsive space operations is the availability of standardized payload accommodations that can simplify integration tasks and reduce costs. Several such standards are beginning to emerge in the very small end of the payload market that is characterized by the so-called CubeSat class of spacecraft. These also happen to be compatible with proposed nanosat launch vehicle (NLV) concepts that are intended to enable dedicated CubeSat missions that are free from the operational constraints associated with traditional secondary payload manifest opportunities. The Poly-Picosatellite Orbital Deployer (P-POD) under development by California Polytechnic State University, San Luis Obispo is one such system that is now transitioning to flight status. The viability and merits of such dedicated CubeSat missions was highlighted recently during flight testing of the Prospector 7 NLV-sized prototype reusable launch vehicle that was developed by Garvey Spacecraft Corporation and California State University, Long Beach. In this case, an engineering prototype of the P-POD unit manifested and then deployed a set of three simulated CubeSats twice within a period of just 3.5 hours. The entire program took only six months. Future plans envision extending the operational environments that the P-POD will be evaluated under as NLV development transitions to higher-performance vehicles. Besides the evaluation of refined payload accommodations and integration techniques, CubeSat payloads will help monitor and characterize NLV environments. Concurrently, participating students will continue to gain valuable experience with flight hardware integration and operations.

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A key factor for responsive space operations is the availability of standardized payload accommodations that can simplify integration tasks and reduce costs. Several such standards are beginning to emerge in the very small end of the payload market that is characterized by the so-called CubeSat class of spacecraft. These also happen to be compatible with proposed nanosat launch vehicle (NLV) concepts that are intended to enable dedicated CubeSat missions that are free from the operational constraints associated with traditional secondary payload manifest opportunities. The Poly-Picosatellite Orbital Deployer (P-POD) under development by California Polytechnic State University, San Luis Obispo is one such system that is now transitioning to flight status.

The viability and merits of such dedicated CubeSat missions was highlighted recently during flight testing of the Prospector 7 NLV-sized prototype reusable launch vehicle that was developed by Garvey Spacecraft Corporation and California State University, Long Beach. In this case, an engineering prototype of the P-POD unit manifested and then deployed a set of three simulated CubeSats twice within a period of just 3.5 hours. The entire program took only six months.

Future plans envision extending the operational environments that the P-POD will be evaluated under as NLV development transitions to higher-performance vehicles. Besides the evaluation of refined payload accommodations and integration techniques, CubeSat payloads will help monitor and characterize NLV environments. Concurrently, participating students will continue to gain valuable experience with flight hardware integration and operations.

BACKGROUND

Garvey Spacecraft Corporation (GSC) and California State University, Long Beach (CSULB) are partnered in the development of a nanosat launch vehicle (NLV) that would provide low-cost flights for payloads of up to 10 kg to low Earth orbit.[1, 2] This effort is characterized by an active, incremental flight program with full-scale, increasingly sophisticated NLV prototypes (Fig. 1).

Figure 1. Prototype NLV Missions Provide a Mechanism for Refining Payload Accommodations

Initials concepts for NLV payload accommodations focused on missions dedicated to manifesting a single "large" nanosat-class (i.e. - 10 kg) deployable spacecraft (Fig. 2). Informal feedback showed a strong preference for low-shock attachment/separation assemblies like those provided by Planetary Systems Corporation[3] and Starsys Research Corporation versus the traditional, high-shock nine inch diameter V-band clamp systems originally introduced on early Delta secondary payload missions.

Figure 2. Early NLV Payload Accommodation Studies Focused On Single 10 kg-Class Spacecraft

Possibly more significant from a business perspective has been the recognition of the potentially substantial but as yet not fully quantified market niche for responsive missions involving the deployment of multiple smaller (1 kg) CubeSat spacecraft.[4] The emergence of this opportunity can be attributed in large part to the efforts by California Polytechnic State University, San Luis Obispo (Cal Poly SLO) to manifest on the order of up to 15 such CubeSats at a time as commercial secondary payloads aboard Dnepr rockets.[5]

Even though economically attractive at first consideration, such secondary positions are still constrained by the CubeSat user's lack of choice relative to deployment altitude, orientation, orbit and date of launch. As a consequence, NLV flight test priorities in this area have shifted so as to first better understand and to then satisfy the needs of the CubeSat user community for more user-friendly services.

The first step in this direction involved a quick study on the feasibility of adapting the Cal Poly SLO Poly-Picosatellite Orbital Deployer (P-POD) for use with the NLV, with each P-POD being able to carry three standard CubeSats (Fig 3). Preliminary results indicated that at least one such P-POD could be manifested with minimal engineering work. Manifesting up to three P-PODS appears to be viable from a volume perspective, but will require additional re-engineering of the P-POD housing as well as the NLV fairing assembly to achieve the full complement of nine CubeSats possible with such a configuration.

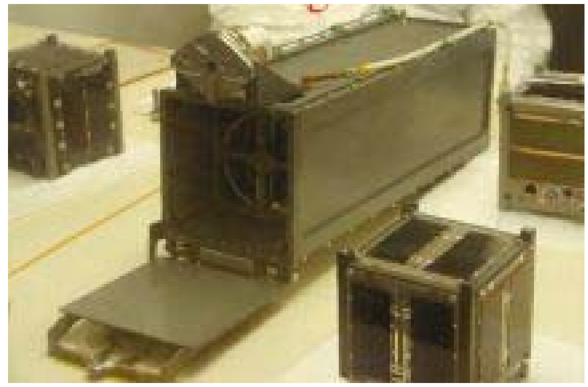

Figure 3. Cal Poly SLO P-POD with Three CubeSats Undergoing Preparation for Integration

INITIAL P-POD PATHFINDER FLIGHT TESTS

To push beyond purely paper and CAD-based payload accommodations concepts, GSC and CSULB teamed with Cal Poly SLO to manifest and evaluate P-POD functionality and associated ground operations on an early prototype NLV flight test. The first such opportunity was with the Prospector 7 (P-7) vehicle that GSC and CSULB developed under a Phase I SBIR contract sponsored by the Air Force Research Laboratory's Propulsion Directorate at Edwards Air Force Base.[6, 7] Of particular value for the P-POD demonstration was the fact that the P-7 was/is a prototype reusable launch vehicle (RLV) that was designed specifically for conducting responsive, fast turn-around launch operations. The implication was that the P-POD test team would have the opportunity to conduct two flight-based tests in a single day, but with only hours instead of weeks, months or years to recover, refurbish and prepare their hardware for the second flight.

In true responsive launch fashion, P-POD integration started in earnest just several months before launch (the entire P-7 development and flight campaign took only six months). For this test, a single P-POD deployer was mounted on the aft end of a composite bulkhead that was installed on the aft end of the P-7's interstage,[†] with

[†] *The "interstage" is so named because in the operational NLV configuration such a structure is located between the first and second stages (the black section of the Prospector 6 vehicle shown in Fig. 1). The P-7 lacks a second stage but the interstage structure has been retained for other reasons.*

the CubeSat deployment direction perpendicular to the vehicle's central axis. Fig. 4 shows two of the Cal Poly SLO and CSULB students after they have completed the P-POD integration and functional check-out in the CSULB development lab at T-6 days, while Fig. 5 presents a close-up view of the deployment port while the vehicle is in flight. It is anticipated that in an operational NLV, the mounting location would be at the top end of the second stage, within the fairing.

Figure 4. P-POD Integration Underway at CSULB

Figure 5. Close-up View of P-POD Deployment Port at the Aft End of the P-7 Interstage

The P-7 flight testing with the P-POD unit took place on 29 October 2005 in the Mojave desert after less than 18 hours of on-site launch preparations. The vehicle was successfully recovered after both flights (Fig. 6 and 7), with only 3.5 hours required for turn-around operations. In addition to the Cal Poly SLO P-POD payload, it also manifested a data logger experiment provided by Montana State University that successfully measured the vehicle flight dynamics and environments on both flights. In contrast to orbital missions, students from both schools then returned to their home campuses with their hardware intact and available for future flight tests.

Figure 6. P-7 In Flight With P-POD Deployer

Figure 7. P-7 In Flight Again - 3.5 Hours Later

CUBESAT FIELD SITE INTEGRATION OPERATIONS

Cal Poly's development and finalization of the P-POD demonstration experiments for the P-7 flights took only three weeks from the start of hardware-related tasks. This was made possible in large part because of the availability of existing equipment that could be pulled off the shelf and used for flight. The first experiment consisted of three simulated CubeSats while on the second experiment, one of the mock satellites featured a small parachute. The selected P-POD was fitted with a release mechanism from an older unit while four L-brackets were also added to attach the P-POD securely to the mounting plate. As noted previously, the P-POD was delivered to CSULB for mounting and fit checks less than one week before launch.

Final integration activities took place at the test site the night before launch, with the back of a pickup truck proving to be entirely adequate as the P-POD work area (Fig. 8).

Figure 8. P-POD First Flight Final Integration Underway the Evening Before Flight Testing

Among the issues that arose was the need to replace a faulty deployment switch that was damaged during a test run. Voltages were also taken to insure the reliability of the electronics. Low-cost rechargeable batteries to power the release mechanism were then secured to the mounting plate using simple but effective plastic tie wraps in place of specially machined mounting brackets (Fig. 9).

Figure 9. Low-cost Approach to Mounting the P-POD Batteries

As their CSULB counterparts focused on the P-7, the Cal Poly students completed these integration activities by loading the first three mock satellites into the P-POD and setting the release mechanism. Total integration time took only two hours.

Launch day operations for the first flight consisted of another set of subsystem voltage checks and verification of the electrical continuity of the line tension, line cutter cover, and break wire. Upon removal of the remove-before-flight saftey pin the P-POD was ready for launch. The deployment sequence itself was initiated by separation of an electrical quick-disconnect connector at the base of the P-7.

Successful deployment of all three mock satellites from the P-POD was achieved on the first flight, with their ejection from the vehicle taking place within the predicted time frame of T+37 seconds. A significant observation was that these simulated CubeSats were ejected far enough from P-7 to avoid collision with both the vehicle and its drogue and main recovery parachutes.

Upon return of the P-7 to the launch site for turn-around operations, the composite bulkhead with the P-POD was completely removed from the vehicle for detailed inspection. One deployment switch, which was set up to cut power to the release mechanism upon successful deployment, was found to be damaged and was replaced, and the two mock satellites and satellite structure with a parachute were placed into the P-POD. The battery voltage for the deployment electronics was again checked, and the mounting bulkhead was re-integrated as planned into a new interstage for the second flight. Given the lessons learned from the previous evening and availability of sunlight, the Cal Poly students only needed 1.5 hours this time to complete their tasks. Instead of a truck, a fold-out table served as the main P-POD work area (Fig. 10).

Figure 10. CubeSat Integration Underway Between Flights

The second launch again saw a successful deployment of all three payloads. The CubeSat parachute worked acceptably, engaging approximately 1 second after ejection. When recovered, the P-POD had all of its parts fully intact, despite once more experiencing a major shock when the P-7 impacted the lake bed fairing-first as designed (Fig. 11).

Figure 11. The P-7 Just Prior to Landing After Its Second Flight

NEXT STEPS

With at least nine more low- and medium-altitude suborbital NLV flight tests scheduled over the next two years, there will be numerous opportunities to further test, iterate and re-test candidate responsive CubeSat payload accommodation concepts. Preliminary planning is already underway to re-fly the same P-POD unit from the first P-7 flights aboard another upcoming P-7 mission. This time, the unit will deploy an active, deployable Cal Poly SLO sensor package to monitor the launch environment as well as evaluate the viability of license-free, spread-spectrum wireless technology for a store-and-forward telemetry downlink. If successful, such a product could become a standard part of the vehicle special instrumentation on future NLV flight tests. In parallel, attention is also being given to experiments involving Ecliptic Enterprises Corporation's RocketPod™ for deploying single CubeSats.

Besides vehicle hardware, another candidate area for improving responsive CubeSat launches operations and reducing costs involves the implementation and utilization of flexible data networks. Emerging satellite-based commercial broadband services now make it possible to reduce the size of the on-site field team while also involving a greater number of participants who might not otherwise get the chance, such as new students who do not yet qualify for the travel team. The first limited trial of such functionality took place during the initial round of P-7 flight testing, as depicted by the DirecTV antenna dish that is in the foreground of Fig. 11. CSULB students are now finishing tailored web pages and telemetry formats for the next P-7 flight test.

On a broader scale, the small size of the NLV payload accommodations and second stage merits consideration of entirely new approaches to payload integration. Rather than delivering the individual CubeSats to the field site for final integration and checkout, as was done on the initial P-7 flight campaign and is baselined for Dnepr flights at the Baikonur Cosmodrome, it should be possible to instead conduct most of these tasks back at the primary customer's facility. The encapsulated assembly could then be shipped to the launch site by van or SUV, under the control of the principal investigator right up through final mating with the launch vehicle. The demonstration and refinement of such an end-to-end CubeSat integration process is a high team priority and has a good chance for an initial trial run in 2007, with Cal Poly SLO serving as the CubeSat integration site.

One possible outcome of these near-term design and operational evaluations is the development of a unique NLV second stage configuration that is optimized specifically for the multiple CubeSat deployment mission. For example, the switch to a shorter, fixed fairing would eliminate the costs and complexity associated with a deployable fairing and its separation mechanism, while it should be possible to merge the basic deployer housing structures into that of the second stage to further reduce total vehicle mass. Relative to avionics, implementing the P-POD power, telemetry, command and data handling functions with those equivalent subsystems already on the second stage presents another opportunity to reduce part count, cost and mass.

CONCLUSION

Results from this first set of flight demonstrations and evaluation of a candidate approach to CubeSat payload accommodations aboard the Prospector 7 prototype NLV has provided preliminary validation that the small size of these systems is indeed an enabling factor for operationally responsive, low-cost launch. Relative to CubeSat payload processing, it is now estimated that with sufficient preparation and practice, integration could be completed for each P-POD in under 30 minutes.

At a higher level, the ability to continue such iterative testing on a frequent basis - in some cases with literally just hours between flights - stands in marked contrast to existing space test programs which are characterized by cycle times that are measured in years. All efforts will be made to retain this degree of responsiveness in the future as NLV testing evolves to more sophisticated and higher performance missions.

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